Final Report for LTSA Grant NAGW-3280

# Compact Objects and Binaries in Globular Clusters and the Galaxy

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# 1 INTRODUCTION

Over the first three years (FY93-FY95) of this LTSA grant NAGW-3280, we have conducted a study of *Compact Objects and Binaries in Globular Clusters and the Galaxy.* Our work is continuing under the new LTSA grant (NAG5-3256) for the originally granted years 4 and 5. In this Final Report, we summarize the work carried out for the first 3 year grant period.

This LTSA grant has provided partial support for much of our work on the nature and evolution of compact objects and compact x-ray binaries in globular clusters and in the Galaxy. A number of significant results were obtained, and are continuing under the new grant.

# 2 SIGNIFICANT RESULTS ACHIEVED

## 2.1 Globular Clusters

Our studies of dim x-ray sources and compact binaries in globular clusters has emphasized the post core collapse globular NGC 6397, which we have studied with both ROSAT and HST. During the final year of this grant, our long-awaited HST Cycle 4 spectroscopic study with the HST FOS was carried out. This followed up our our earlier imaging studies which had revealed candidate cataclysmic variables (CVs) in this globular; and a very deep ROSAT HRI observation of the same cluster. Other studies were also completed or initiated.

The following are the principal globular cluster projects carried out over the grant:

1. **HST Spectra of CV candidates in NGC 6397**
   We obtained FOS spectra of the three brightest CV candidates, discovered in our Cycle 2 WFPC1 imaging (H$\alpha$ vs. R) as described in Cool et al (1995). Results are presented in Grindlay et al 1995 and Grindlay (1996) and show that not only are these objects indeed H$\alpha$ emission line objects but that they also have strong He I and He II emission indicative of them being possibly magnetic CVs. If so, this is a major discovery that we hope to followup with additional HST observations as proposed for Cycle 6.

2. **Deep HRI Observation of NGC 6397**
   We have received the data for our deep ROSAT observation (75 ksec) of NGC 6397. Preliminary analysis (Grindlay 1996) shows that at least 6 sources are contained within ~10 arcsec of the

cluster center and that at least one of these is a likely x-ray counterpart of one of the fainter H$\alpha$ objects found in our HST studies (Cool et al 1995). More detailed analysis of these rich data is in progress.

3. **Discovery of Diffuse Emission in NGC 6752**
Our study of NGC 6752 (Grindlay and Cool 1996b) has also revealed two sources of diffuse x-ray emission most probably associated with the cluster. This emission may be similar to the diffuse emission we have published (Krockenberger and Grindlay 1995) for 47 Tuc, which is almost certainly due to the bow shock setup by mass loss from the cluster which encounters the ISM of the galactic halo. If so, we predict the cluster is moving with apparent proper motion to the North.

4. **Final Analysis of CGRO Data on NGC 6397 and NGC 6752**
We have completed our analysis of Compton Gamma-ray Observatory Data (CGRO) on the two globular clusters NGC 6397 and NGC 6752. Both COMPTEL and EGRET data were analyzed to derive upper limits for gamma-ray emission from each globular (Manandhar, Grindlay and Thompson 1995) that are a factor of 2 more sensitive than any previously and which limit the gamma-ray luminosity of "typical" millisecond pulsars or quiescent LMXBs to be below $\sim 10^{33-34}$ erg/s.

5. **Analysis of Millsecond Pulsar Pulse Profiles in/out of Globulars**
R. Jayawardhana (Harvard graduate student) carried out a project to systematically examine the pulse profile shapes for millisecond pulsars (MSPs) in and out of globular clusters. This project was to test theoretical suggestions that the possibly different formation mechanism of MSPs in globulars, where they may form more easily by accretion induced collapse of white dwarfs, leads to systematically different magnetic field geometries on the neutron star and thus pulse shape. Evidence was indeed found for a systematic difference in the present sample of some 27 MSPs in globulars vs. a comparable number in the disk. Results were presented (Jayawardhana and Grindlay 1996) at IAU Colloquium 160 on MSPs.

6. **Re-Analysis of Einstein Data on Bright LMXBs in Globulars**
J. Bloom (Harvard undergraduate) carried out a re-analysis of the 7 globular clusters observed with the Einstein Observatory to search for evidence of second sources in these clusters. The analysis made use of improved image analysis techniques and set interesting limits on the presence of multiple LMXBs in single clusters as well as provided an updated derivation of the maximum liklihood analysis for LMXB masses in globulars using improved values of cluster centers and core radii or scaling parameters over those used in our original analysis.

## 2.2 Galactic LMXBs

We have completed analysis of our long-term optical database for the 50-min binary and ultra-compact system 4U1915-05. We extended our studies of the peculiar ultra-compact LMXBs 4U1915-05 and 4U1820-30 to hard x-ray energies using CGRO and have initiated two major prjects with the BATSE instrument on CGRO: studies of x-ray bursters and of black hole transients. The principal projects were as follows:

1. **Studies of the Optical Period of 4U1915-05**
   Our analysis of the optical period and its long-term stability for this possible triple system was completed and published (cf. Callanan, Grindlay and Cool 1995). The results strongly confirm our earlier claims that the optical period is extremely stable, with phase stability now over a total of 7 years of data, and thus the likely binary period of this system. In this case, the shorter x-ray dip period is difficult to understand as a precession period of an eccentric disk (as in SU UMa CV systems or even black hole x-ray novae, for which the binary period is always the shorter period) and may require our earlier proposal that 4U1915-05 is a hierarchical triple system.

2. **Studies of X1916-05 and 4U1820-30: Hard X-ray Spectrum**
   We have carried out the first study of the ultra-compact LMXBs 4U1916-05 and 4U1820-30 using the BATSE instrument on CGRO (Bloser et al 1996). Upper limits (20 - 100 keV) were obtained that, particularly for 4U1915-05, were surprising in view of the extrapolated lower energy (hard) spectrum. More sensitive upper limits still were derived from our separate observations with OSSE on CGRO (Barret et al 1996) and require the spectrum to break at energies below $\sim$60 keV.

3. **Survey of of X-ray Bursters with BATSE**
   We have initiated a major study of the hard x-ray spectra of x-ray bursters using the BATSE detectors on CGRO. This study is intended to followup on the earlier indications with the SIGMA telescope on GRANAT that bursters – particularly in their low states – are detectable hard x-ray sources. Preliminary results for 5 different bursters were presented by Barret et al (1996) and several other detailed investigations are in progress.

4. **Survey of X-ray Transients with BATSE**
   We have also begun a parallel study of faint x-ray transients with the BATSE detectors on CGRO. The goal of this ongoing project is to measure the black hole binary content of the Galaxy. Initial results suggest that the number of faint transients may be less than expected from simple scaling of the bright source results to the greater distances possible to search in the Galaxy. The overall project is described by Grindlay et al (1996).

In addition we carried out a project (with E. Maoz) on the possible origin of the cosmic diffuse x-ray background, as measured at the faintest x-ray fluxes with ROSAT, from a population of faint sources in the galactic halo. We showed (Maoz and Grindlay 1995 and Grindlay and Maoz 1996) that a halo, or thick disk, population of CVs with typical x-ray luminosities of $\sim 10^{31}$ erg/s would be fully consistent with the known constraints on the CXB.

# 3 Students and Collaborators

Our work under this grant has primarily focussed on both ROSAT and HST observations of globular clusters. This has been carried out with former graduate students A. Cool (Berkeley), C. Bailyn (Yale), and P. Hertz (NRL) as well as collaborators at Indiana University (H. Cohn and P. Lugger). Two Harvard graduate students (M. Krockenberger and R. Jayawardhana) and one undergraduate (J. Bloom) have been supervised on different projects relating to compact binaries in globular clusters. We have also initiated two major studies of x-ray bursters and black hole transients in the Galaxy.

These have been in collaboration with D. Barret (postdoc) and P. Bloser (Harvard graduate student) as well as collaborators on the BATSE team at MSFC.

# 4 PAPERS PREPARED UNDER GRANT


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2. Barret, D., Grindlay, J., Strickman, M. and Vedrenne, G. 1996, "OSSE Observations of the X-ray Burster 4U1915-05", *Astronomy and Astrophysics, Supplement Series*, in press.

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4. Callanan, P.J., Grindlay, J.E. and Cool, A.M. 1995, "Optical Studies of X1916-05", PASJ, 47, 1.

5. Cool, A., Grindlay, J. Krockenberger, M. and Bailyn, C. 1993, "Discovery of Low Luminosity X-ray Sources in NGC 6397", in *Structure and Dynamics of Globular Clusters*, (S. Djorgovski and G. Meylan, eds.), ASP Conference Series, Volume 50, pages 307-308.

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15. Grindlay, J.E. 1995, "X-ray Sources vs. Millisecond Pulsars in Globular Clusters", in "Millisecond Pulsars: A Decade of Surprise", ASP Conf. Series, 72, 57.

16. Grindlay, J.E. et al 1995, "Spectroscopic Identification of Probable CVs in NGC 6397", *Ap. J. Letters*, in press (Dec. 10, 1995 issue).

17. Grindlay, J.E. 1996, "High Resolution Studies of Compact X-ray Binaries in Globulars With ROSAT and HST", in *Proc. IAU Symp. 174*, (P. Hut and J. Makino, eds.), pp. 171-180..

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